The bright optical companion to the eclipsing millisecond pulsar in NGC 6397[1]

Francesco R. Ferraro, Andrea Possenti, Nichi D'Amico, Elena Sabbi
Osservatorio Astronomico di Bologna, via Ranzani 1,I–40126 Bologna, Italy

Received by ApJ Letters on 31 July, 2001

ABSTRACT

We report the possible optical identification of the companion to the eclipsing millisecond pulsar PSR J1740−5340 in the globular cluster NGC 6397. A bright variable star with an anomalous red colour and optical variability which nicely correlates to the orbital period of the pulsar has been found close to the pulsar position. If confirmed, the optical light curve, reminiscent of tidal distorsions similar to those observed in detached and contact binaries, support the idea that this is the first case of a Roche lobe filling companion to a millisecond pulsar.

Subject headings: Globular clusters: individual (NGC6397); stars: evolution – binaries: close; pulsars: individual (PSR J1740−5340) stars: millisecond pulsar

1. Introduction

The millisecond pulsar (MSP) PSR J1740−5340 was discovered during a systematic search of the globular cluster (GC) system for millisecond pulsars, carried out with the Parkes radiotelescope (D'Amico et al. 2001a, 2001b). The pulsar, associated with the globular cluster NGC6397, is member of a binary system with a relatively wide orbit of period $\simeq 1.35$ days, and it is eclipsed for about 40% of the orbital phase at 1.4 GHz. In a companion paper, D'Amico et al. (2001c) provide strong evidences that the companion star could be an unusual object, and give a precise position for the pulsar.

We here present the results of a deep search of the optical companion to PSR J1740−5340 in the HST archive.

[1]Based on observations with the NASA/ESA HST, obtained at the Space Telescope Science Institute, which is operated by AURA, Inc., under NASA contract NAS5-26555

2. Observations and data analysis

The photometric data consists of a series of public HST exposures taken on March 1996 and April 1999, retrieved from the *ESO/ST-ECF Science Archive*. The 1999 observations consist of 116 WFPC2 exposures with filters F555W, F675W, F814W and F656N (referred here as $V_{555}, R_{675}, I_{814}$ and Hα), spanning about 1.8 days. The 1996 observations consist of 55 exposures with filters F336W and F439W (referred here as U_{336} and B_{439}), spanning 0.4 and 0.2 days respectively.

From the accurate timing position (RAJ $17^{\rm h}\ 40^{\rm m}\ 44\overset{\rm s}{.}589$; DECJ $-53^o\ 40'\ 40\overset{''}{.}9$) the MSP in NGC6397 turns out to be approximately at $29''E$ and $16''S$ from the cluster center (Djorgovski & Meylan 1993). We used the STSDAS program *metric*, to roughly locate the MSP in the retrieved WFPC2 images, and it turns out to be within the field of view of the WF4 chip in both the data set.

2.1. Astrometry

The exact location of the MSP in the HST images was obtained by searching an astrometric solution for a wide field CCD image of a region around NGC 6397. We retrieved from the *ESO Science Archive* an image obtained on May 1999 with the Wide Field Imager (WFI) at the ESO 2.2m telescope (at European Souther Observatory, La Silla, Chile). The entire image consists of a mosaic of 8 chips (each with a field of view of $8' \times 16'$) giving a global field of view of $33' \times 34'$. Only the chip containing the cluster center was used. The new astrometric *Guide Star Catalog* (*GSCII*) recently released and now available on the WEB, was used to search for astrometric standard lying in the WFI image field of view: several hundreds astrometric *GSCII* reference stars have been found, allowing an accurate absolute positioning of the image.

In order to derive an astrometric solution for the WFI image we used an appropriate procedure developed at the Bologna Observatory. The resulting rms residuals were of the order of $\sim 0.3''$ both in RA and Dec. By using this astrometry we were able to accurately locate the nominal position of the MSP in the WFI image and in the HST-WFPC2 images.

Fig. 1 shows an enlargement of a $7'' \times 7''$ region of the WF4 chip, centered on the MSP position. The 3σ error circle, which takes into account the global error in the absolute positioning of the MSP, is shown. The global error is fully dominated by the uncertainty due to the astrometric procedure. One relatively bright star (A) has been found within the error box of the MSP. Two additional objects (B, C) are just out-side the error circle. In order to investigate the nature of these objects we performed accurate photometric analysis of the entire HST-WFPC2 data-set retrieved from the Archive.

2.2. Photometry

The photometric reductions have been carried out using ROMAFOT (Buonanno et al. 1983), a package developed to perform accurate photometry in crowded fields and specifically optimized to handle under-sampled point spread function (PSF) as in the case of the HST-WF chips (Buonanno & Iannicola 1989). The standard procedure described in Ferraro et

al. (1997) was adopted in order to derive PSF-fitting instrumental magnitudes, which were finally calibrated using zero-points listed by Holtzman et al. (1995). In particular we used a sample of median-combined images to construct reference Color Magnitude Diagrams (CMDs). Figure 2 shows multiband CMDs for stars detected in a region of 400 × 400 pixels (corresponding to $40'' \times 40''$): the location of the three objects are indicated.

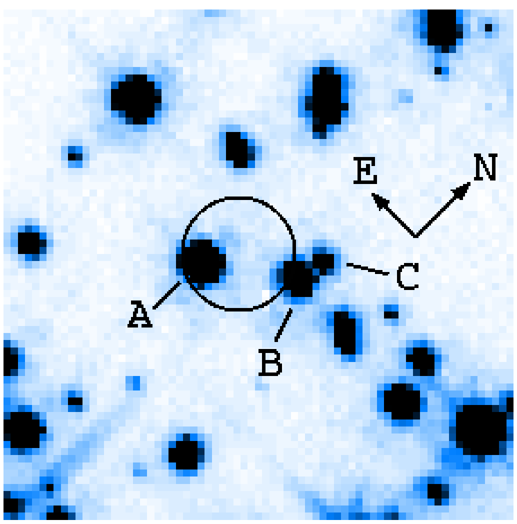

Fig. 1.— A portion of a median-combined F675W HST WFPC2 image (chip WF4) of NGC 6397, centered near the MSP position. The region covers about $7'' \times 7''$. Star A is the proposed companion to the MSP PSR J1740−5340.

The result of the PSF fitting procedure for these stars have been carefully examined by visual inspection. From this accurate photometric analysis we found that the bright object A lying within the error box of the MSP has an anomalous position in the CMD since it is located at the luminosity of the TO region but it has an anomalous red colour; the other two objects (B, C) are normal Main Sequence stars. Individual images were instead used to check the variability of the objects. Objects B and C show no significant time variability compared to the measurements uncertainties. On the other hand, object A shows a remarkable time modulation ($\sim 0.2 - 0.3$ mag) on a scale of several hours. This object is the variable star WF4-1 proposed by Taylor et al. (2001) as a BY Draconis star.

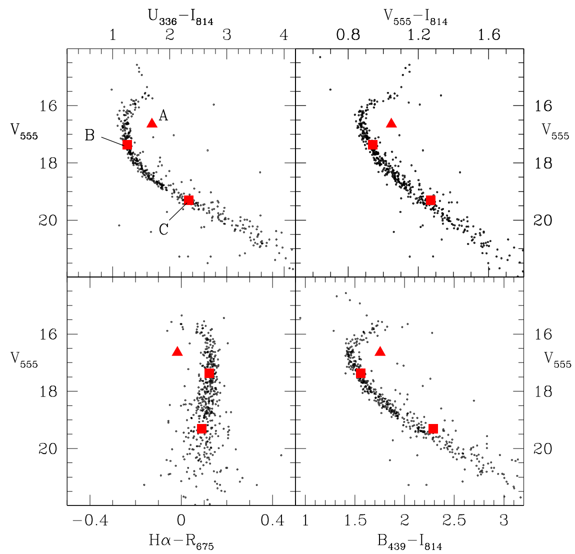

Fig. 2.— Multiband CMDs for stars detected in a region of the WF4 chip ($40'' \times 40''$) containing the MSP position. The three stars found in the vicinity of the MSP error box are marked with different symbols (a triangle for star A and squares for stars B and C) and labeled with their names in the first panel.

2.3. Time series

In order to check the association of the time variability of Star A to the pulsar binary motion, we have carried out a period search analysis. The data available consist of four time series in the Hα, R_{675}, I_{814}, and V_{555} bands taken in 1999, spanning $\sim$ 1.8 days, and two time series in the B_{439}

and U_{336} bands taken in 1996, spanning 0.2 and 0.4 days, respectively. The periodicity search was carried out using GRATIS (GRaphycal Analyzer of TIme Series), a software package developed at the Bologna Astronomical Observatory (see Clementini et al. 2000, 2001). Periods and amplitudes were derived for the Hα-band time series using GRATIS χ^2 Fourier fitting routine. This algorithm is almost equivalent to the Lomb-Scargle periodogram (Scargle 1982), but has the advantage to have sensitivity also to periodicities whose light curve is not strictly sinusoidal, and it is more reliable when the data span is of length comparable to the time scale of the stellar variation (Faulkner 1977). As already mentioned, the data span of the Hα-band time series is $\sim$ 1.8 days, and the searched periodicity is 1.35 days, so the χ^2 fitting method is largely preferable.

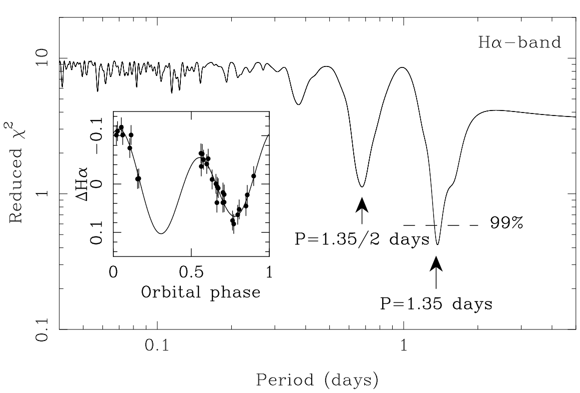

Fig. 3.— Reduced χ^2 resulting from the Fourier fitting of the Hα data as a function of the modulation period. Small panel: light curve of the Hα data obtained adopting the period and the reference epoch of the radio ephemeris and fitting the spectral amplitudes of the 1^{st} and 2^{nd} harmonics.

Fig. 3 shows the reduced χ^2 resulting from the Fourier fitting of the Hα data as a function of the modulation period. The most significant feature is indeed a periodicity around the predicted period of 1.35 days, with substantial power also near the 2^{nd} harmonic. The confidence level peak (99.6%) corresponds to a period P=1.37$\pm$0.05 days (consistent, within the uncertainties, with the period quoted by Taylor et al. (2001) for the WF4-1 variable). The quoted uncertainty corresponds to the period range for which the confidence level is larger than 99%, and it is dominated by the relatively short ($\sim$ 1.8 days) data span available.

Using another option of the GRATIS package, we have then fixed the period P and the reference epoch T_0 to the radio ephemeris values, and have fitted the same Hα data for the best spectral amplitudes of the 1^{st} and 2^{nd} harmonics. The best-fit light curve, shown in the small panel in Fig. 3, is not exactly what we would expect on the basis of a simple pulsar-irradiation model, but as we will discuss in the next section, it could be understood in term of tidal distorsion effects occurring in the companion star to PSR J1740-5340. The time variability observed in the R, I, and V-bands at the same epochs follows a similar pattern to that observed in the Hα-band, and the period search analysis produces similar results. Fig. 4 shows the same 1999 Hα-band data and the U_{336}-band data taken on 1996, phased using the accurate radio ephemeris. Remarkably, they show the minimum at the same orbital phase, giving further evidence that the optical modulation is indeed associated to the pulsar binary motion.

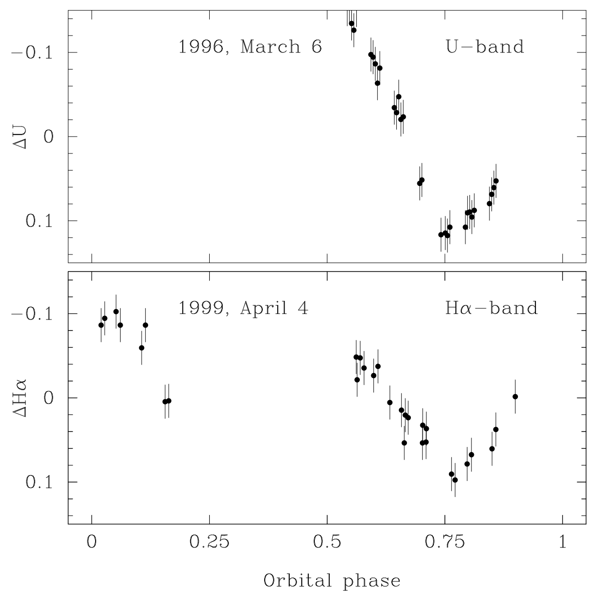

Fig. 4.— Hα-band data and U_{336}-band data, taken 3 yr a part, phased using the radio ephemeris. Phase 0.0 corresponds to the time of the ascending node.

2.4. Is Star A the pulsar companion?

Can we claim that Star A (WF4-1) is not a BY Draconis system but is indeed the optical companion to the MSP? There is no doubt that Star A is variable, and that the modulation period is compatible to the radio orbital period. However is difficult to estimate the chance occurrence probability to find a variable star with a period of $\sim 1.3-1.4$ days in such a small error circle. HST observations (Taylor et al. 2001) have discovered several variables in a WFPC2/HST field of view. Also, according to Taylor et al. (2001), a modulation period of the order of ∼day is typical of most BY Dra systems.

On the other hand, in two observations taken three years a part, we find the minima exactly at the same phase with respect to the precise radio orbital period, whilst the light curve shape of the BY Dra systems are expected to change, according to variations in the configuration of the spotted regions (Alekseev 1999) of their convective envelopes. Also, the position of Star A in the CMD is anomalous for a BY Dra or whichever other kind of binary system comprising two MS stars. Further support to the proposed association derives from the detection of PSR J1740-5340 in a *Chandra* pointing of NGC 6397 (Grindlay et al. 2001b): its X-ray luminosity and color appear similar to those of the MSPs seen in 47 Tuc (Grindlay et al. 2001a) and its positional coincidence with Star A is consistent with the *Chandra* astrometric uncertainties.

3. Observed properties of the companion star

In the radio timing paper, D'Amico et al. (2001c) demonstrate that the companion star can not be the typical WD found in most binary MSPs. They propose that the companion can be a MS star acquired by exchange interaction in the cluster core or alternatively the same star that spun up the MSP and that would be still overflowing its Roche lobe. Assuming that Star A is the pulsar companion, we here discuss these two hypotheses, comparing them with observed optical properties of Star A .

In order to get some quantitative hints on the effective temperature T_{eff} and the radius R_c of Star A , we used the recent set of isochrones by Silvestri et al. (1998) and by Vanderberg (2000). By comparing the CMDs in Fig. 2 with those isochrones, for metallicity [Fe/H]=-2.00 and ages of $t = 12 - 14$ Gyr, (compatible with the values

measured for NGC 6397), we derive $R_c \sim 1.3 - 1.8$ $R_\odot$ and $T_{eff} \sim 5500 - 5800$ K for Star A .

The peculiar nature of Star A can be unveiled inspecting the amplitude and the shape of its light curves (Figure 3, 4). There are 2 other eclipsing MSPs (PSR B1957+20 (Callanan, van Paradijs & Rengelink 1995) and PSR J2051-0827 (Stappers et al. 1999)), both in the Galactic field, whose optical companion displays strong modulations, interpreted as due to the heated side of the companion entering in and out of view according to the orbital motion. Similar trend, though with a much smaller degree of modulation, is seen in 47 Tuc U_{opt}, the first identified MSP companion in a GC (Edmonds, et al. 2001).

The light curves of Star A are completely different. We locate the phase 0.0 at the ascending node of the MSP orbit; thus at the phase 0.75 we see the side of the companion facing the pulsar. In contrast to the other known variable MSP companions, the light curves of Star A display there a minimum instead of a maximum (see Figure 4). Within the limits in the orbital period coverage of our photometry, the best-fit light curve of Figure 3 shows two maxima and two minima during each binary orbit: thus, tidal distorsions appear the more natural responsible for this shape. They have been already invoked for explaining the light curves of the optical companions to black-hole candidates (van der Klis, et al. 1985) and NSs (Zurita, et al. 2000). In this scenario the maxima correspond to quadratures (phases 0.0 and 0.50), when the distorted star presents the longest axis of its ellipsoid to the observer, the minima to the conjunctions. It is easy to recognize this trend in the insert of Figure 3.

Whether this is the correct interpretation, it turns out in severe constraints on the mass and the nature of Star A. The degree of ellipsoidal variations depends roughly on (Russell 1945) $\Delta m = k_\lambda (M_{MSP}/M_c)(R_L/a)^3 F^3 \sin^2 i$, where M_{MSP} and M_c are the masses of the MSP and its companion, R_L is the Roche lobe radius of the companion, a is the orbital separation, F is the ratio between the average radius of the star and the Roche lobe radius and i is the inclination of the orbit. The term $k_\lambda = 2.6$ accounts for limb and gravity darkening for H_α-radiation from our source (Lucy 1967). Given the orbital parameters of PSR J1740-5340 (D'Amico et al. 2001c), it follows $(M_{MSP}/M_c)(R_L/a)^3 \sim 0.07$ for all the possible companions, and thus $\Delta m_{H_\alpha} \lesssim 0.2F^3 \sin^2 i$. As the observed modulation (Figure 4) is just ~ 0.2 mag, we argue that only a companion almost filling its Roche lobe ($F \sim 1$) and nearly edge-on ($i \sim 90^o$) can reproduce that. Remarkably, these two requirements are contemporary accomplished by a companion of mass $\lesssim 0.25$ $M_\odot$, whose Roche lobe radius just matches the lower limit inferred for the observed radius R_c of Star A .

The light curve of a star affected only by tidally distorsion would have the minimum at phase 0.25 less deep than that at phase 0.75. The reversal of this rule in the case of Star A can result from the overheating of the side facing the pulsar. In contrast to 47 Tuc U_{opt} (having $F \sim 0.17$), and to the companions to PSR J2051-0827 and to PSR B1957+20 (for which $F = 0.5$ and $F = 0.9$), Star A fills up its Roche lobe

allowing ellipsoidal variations to dominate over the thermal modulation. A direct detection of both the minima would allow a measurement of the fraction of the impinging power from the pulsar which goes in heating of the surface of Star A , a very interesting value for understanding the composition of the pulsar energetic flux.

4. Discussion

In summary, PSR J1740-5340 appears as the first example of a MSP orbiting a Roche lobe filling companion, whose brightness would allow unprecedented detailed investigations, for example about the origin of this system.

A first hypothesis is that Star A is a MS star perturbed by the energetic flux emitted from the MSP. The so-called *illumination* mechanism (D'Antona 1995) predicts that if the heating luminosity $L_h \lesssim (1/4)(R_*/a)^2 L_{irr}$ (where R_* is the star radius and L_{irr} the MSP luminosity) is large enough, the star inflates and increases the effective temperature, thus modifying its photometric characteristics (Podsiadlowski 1991). The rotational energy loss from the MSP is $L_{irr} \sim 1.4 \times 10^{35}$ erg/s (D'Amico et al. 2001c). At the distance $a \sim 6.5$ R$_\odot$, this corresponds to a characteristic temperature for the heating bath in which the star is immersed $T_h = [1/(16\sigma\pi)L_{irr}/a^2]^{1/4} \lesssim 4000$ K where σ is the constant of Stefan-Boltzmann. We expect that the MSP flux significantly affects the companion only if $T_h \gtrsim T_*$ (where T_* is the effective temperature of an unperturbed MS star) and $T_* \lesssim 4000$ K implies $\lesssim 0.4$ M$_\odot$. As T_h does not depend on R_*, it seems energetically difficult to explain an increasing of $\sim$ 40% of the effective temperature; however, only detailed simulations (Burderi, D'Antona & Burgay 2001, in preparation) of the system will allow to assess if such a low mass MS star of radius $\sim 0.2 - 0.4$ R$_\odot$ can indeed be bloated up to $\lesssim 1.3$ R$_\odot$ and heated from $\sim$ 4000 K to $\sim$ 5500 K by the energetic flux of the MSP.

Another fascinating possibility is that PSR J1740−5340 is a new-born MSP, the first one observed just after the end of the process of recycling. In this case Star A could have been originally a MS star of $1 - 2$ M$_\odot$, whose evolution triggered mass transfer towards the compact companion, spinning it up to millisecond periods (Alpar, et al. 1982). Irregularities in the mass transfer rate $\dot{M}_c$ are common in the evolution of these systems (e.g. Tauris & Savonije 1999): even a short decreasing of $\dot{M}_c$ can have easily allowed PSR J1740−5340 (having a magnetic field $\sim 8 \times 10^8$ G and a rotational period $\lesssim 3.65$ ms) to became source of relativistic particles and magnetodipole emission, whose pressure *(i)* first swept the environment of the NS, allowing coherent radio emission to be switched on (Shvartsman 1970) and *(ii)* then kept on expelling the matter overflowing from the Roche lobe of Star A (Ruderman, Shaham & Tavani 1989). For a wide enough binary system (as is the case of PSR J1740−5340), once the radio pulsar has been switched on, any subsequent restoration of the original $\dot{M}_c$ cannot quench the radioemission (Burderi et al. 2001). In this case we have now a donor star still losing matter from its Roche lobe at $\dot{M}_c \gtrsim 5 \times 10^{-11}$ M$_\odot$/yr, (D'Amico et al. 2001c) (a high mass loss rate, difficult to explain in the model of a

bloated star). At the same time, accretion on the NS is inhibited due to the pressure exerted by the pulsar on the infalling matter. This strong interaction between the MSP flux and the plasma wind would explain also the irregularities seen in the radio signals from PSR J1740−5340, sometimes showing the presence of ionized matter along the line of sight even when the pulsar is between Star A and the observer. The characteristic age of PSR J1740−5340 ($\sim 3.5 \times 10^8$ yr) seems indicating it is a young MSP, further supporting this scenario.

If Star A will continue releasing matter at the present rate $\dot{M}_c$, PSR J1740−5340 is not a candidate for becoming an isolated pulsar. When Star A will have shrunk well inside its Roche lobe, the system will probably end up as MSP+WD (or a light non degenerate companion). If Star A will undergo a significant increasing of $\dot{M}_c$, the condition for the accretion could be reestablished and PSR J1740−5340 would probably appear again as a Low Mass X-ray Binary or as a Soft X-ray Transient (Campana, et al. 1998).

We thank P. Montegriffo for assistance with the astrometry procedure, G. Clementini, L. Burderi and F.D'Antona for useful discussions and Elena Pancino for providing the WFI image. Financial support to this research is provided by the Agenzia Spaziale Italiana (ASI) and the *Ministero della Università e della Ricerca Scientifica e Tecnologica* (MURST). The GSCII catalog was produced by the Space Telescope Science Institute and the Osservatorio Astronomico di Torino. The ESO/ST-ECF Science Archive facility is a joint collaboration of the European Souther Observatory and the Space Telescope - European Coordinating Facility.

REFERENCES

Alekseev, I. Yu. 2000, Astronomy Reports, 44, n^o 10, 696

Alpar, M. A., Cheng, A. F., Rutherman, M. A., and Shaham, J. 1982, Nature, 300, 728

Buonanno, R., Buscema, G., Corsi, C.E.,Ferraro, I., & Iannicola, G. 1983, A&A, 126, 278

Buonanno, R., & Iannicola, G. 1989, PASP, 101, 294

Burderi, L., et al. 2001, in Evolution of Binary and Multiple Star Systems, ed. P. Podsiadlowski, S. Rappaport, A. King, F. D'Antona, & L. Burderi (San Francisco: ASP), 229, 455, astro-ph/0104170

Callanan, P. J., van Paradijs J., & Rengelink R. 1995, ApJ, 439, 928

Campana, S., Colpi, M., Mereghetti, S., Stella, L., & Tavani, M. 1998, A&A Rev., 8, 279

Clementini, G. et al. 2000, AJ, 120, 2579

Clementini, G., Gratto, R. G., Bragaglia, A., Carretta, E., Di Fabrizio, L., & Maio M. 2001, AJ submitted, astro-ph/0007471

D'Amico, N., Lyne, A., Manchester, R., Possenti, A., & Camilo, F. 2001a, ApJ, 548, L171

D'Amico, N., Possenti, A., Manchester, R., Sarkissian, J., Lyne, A., & Camilo, F. 2001b, in Proceedings of the 20th Texas Symposium on Relativistic Astrophysics, American Institute of Physics, in press, astro-ph/0105122

D'Amico, N., Possenti, A., Manchester, R. N., Sarkissian, J., Lyne, A. L., & Camilo, F. 2001c, ApJL, submitted

D'Antona, F. 1995, in Evolutionary Processes in Binary Stars, NATO-ASI Series, ed. R.A.M. Wijers, M.B. Davies, C.A. Tout, Kluwer

Djorgovski, S., Meylan, G., 1993, in Structure and Dynamics of Globular Clusters, ed. S. G. Djorgovski & G. Meylan (ASP: San Francisco), 325

Edmonds, P. D., Gilliland, R. L., Heinke, C. O., Grindlay, J. E., Camilo, F. 2001, ApJ, in press, astro-ph/0107096

Faulkner, D. J. 1977, ApJ, 216, 49

Ferraro, F.R., Paltrinieri, B., Fusi Pecci, F., Cacciari, C., Dorman, B., Rood, R.T.,Buonanno, R., Corsi, C.E., Burgarella, D., Laget, M., 1997a, A&A, 324, 915

Grindlay, J. E., Heinke, C. O., Edmonds, P. D., Murray, S. 2001a, Science, 292, 2290

Grindlay, J. E., Heinke, C. O., Edmonds, P. D., Murray, S. & Cool, A. 2001b, ApJL, submitted

Holtzmann, J.A., Burrows, C.J., Casertano, S., Hester, J.J., Trauger, J.T., Watson, A.M., & Worthey, G. 1995, PASP, 107, 1065

Lucy, L. 1967, Z. Astrophys., 65, 89

Podsiadlowski, P. 1991, Nature, 350, 136

Ruderman, M., Shaham, J., & Tavani M. 1989, ApJ, 336, 507

Russell, H. R. 1945, ApJ, 102, 1

Scargle, J. D. 1982, ApJ, 263, 835

Shvartsman, V.F. 1970, Radiofizika, 13, 1852

Silvestri, F., Ventura, P., D'Antona, F., & Mazzitelli, I. 1998, ApJ 509, 192

Stappers, B. W., van Kerkwijk, M. H., Lane, B., & Kulkarni, S. R. 1999, ApJ, 510, L45

Tauris, T. M., & Savonije. G. J. 1999, A&A, 350, 928

Taylor, J. M., Grindlay, J. E., Edmonds, P. D., & Coll, A. M. 2001, ApJ, 553, L169

Vanderberg, D.A. 2000, ApJS, 129, 315

vand der Klis, M., Clause, J. V., Jensen, K., Tjemkes, S., & van Paradijs, J. 1985, A&A, 151, 322

Zurita, C., Casares, J., Shahbaz, T., Charles, P. A., Hynes, R. I., Shugarov, S., Goransky, V., Pavlenko, E. P., Kuznetsova, Y. 2000, MNRAS, 316, 137

This 2-column preprint was prepared with the AAS LaTeX macros v5.0.